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THE METEORITIC HAZARD OF THE ENVIRONMENT OF A SATELLITE

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SUMMARY

A brief description is made of our knowledge of meteorites, their composition, and frequency of occurrence. A meteoroid flux as a function of mass that has been proposed by F. L. Whipple is compared with the direct measurements obtained to date by rockets, satellites, and space probes. On the assumption of a Poisson distribution for the probability of impacts and a penetration law which represents a mean of those proposed for high-velocity impact, the probability of penetration of earth satellite surfaces is obtained.

INTRODUCTION

The fact that the earth in its movement through space encounters quantities of material of extraterrestrial source was not appreciated until the beginning of the nineteenth century. At that time the simultaneous observation of a meteor by two German students definitely established that these flashes were occurring at heights in excess of 80 kilometers and that the velocities of the particles were of the order of several kilometers per second. The great Leonid shower of 1833 not only aroused great public interest in meteors but also established, by the apparent uniform direction of the trails, that they were produced by particles moving in definite orbits within the solar system. Since 1885 meteorites have been photographed with the intent of establishing their velocity and radiant (direction) and hence, their initial orbits as well as their number count as a function of intensity (visual magnitude). In recent times the most highly organized photographic effort is that of the Harvard Observatory (ref. 1) under the direction of F. L. Whipple. This effort now centered in New Mexico uses Baker-Super Schmidt cameras at separated sites. The cameras are equipped with rotating shutters to determine velocity. They can record meteors of intensity as low as visual magnitude 5, which makes them about as sensitive as the human eye. Several trails can be obtained in an hour of observation.

The development of high power radars during World War II provided a new tool for meteor astronomy when it became apparent that signals were being reflected from the trail of ionized gas in the wake of meteorites. More recent studies have indicated that radar observations are capable of recording meteors as faint as the twelfth magnitude. The fact that the radar measurements are unhampered by cloud cover and daylight not only means a more rapid accumulation of data but also has revealed the existence of daytime showers fully as significant as the nighttime showers.

A second offshoot of World War II, the ballistic rocket, capable of sounding the upper atmosphere and of placing in orbit manmade satellites and space probes, has made possible the direct measurement of meteorites, both at near and extended distances from the earth, by their impact on the shell of the vehicles or on specially installed impact recording devices.

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From the accumulated data, both photographic and radio (the direct measurements are not yet definitive enough), it has been concluded that meteorites striking the earth have been members of the solar system and were originally in orbits about the sun. A small amount of data, less than 1/2 percent, might possibly indicate an extra solar system origin but even this is doubtful. Three possible sources would appear to be responsible for the meteoritic material. There are particles arising from the asteroidal belts which have been perturbed into orbits that intercept the earth, the dust cloud in the plane of the ecliptic whose existence is indicated by the scattered light in the so-called zodiacal light, and the debris left in the orbits of comets. There is strong evidence of cometary origin of shower meteors and Whipple is inclined to believe that both shower and sporadic (random) meteorites are of similar origin. Estimates of the amount of material associated with the zodiacal light indicates more material than would appear to be consistent with the meteorite influx observations. The elementary constituents of the meteorites large enough to fall to earth indicate a distribution compatible with the assumption that they are asteroidal in character and that the asteroids are pieces of a shattered planet. The irons arise from the core and the stones consist of fragments of the surface.

SPORADIC METEORS

The greater portion of the meteor trails that are observed is associated with orbits that are peculiar to each meteor. These trails are in contrast with those of shower meteors which occur annually and for which the orbits and therefore the velocity and radiants cover a narrow range. Considerable theoretical work has been done to predict the distributions of radiants that would be observed if the sporadic meteorites arose from randomly distributed orbits within the solar system. These theories have not been substantiated by observation, and the data indicate that the orbits are predominantly in the plane of the ecliptic. Figure 1, adapted from Lovell (ref. 1), indicates the distribution of orbits about the ecliptic plane. Most of the orbits are contained within $\pm 15^{\circ}$ to 20° of the ecliptic plane. Further, the motion in orbit is mostly direct (same direction as earth moves about sun). Reduction of the data on sporadic meteors yields the distribution in the direction of the orbits at earth's radius shown in figure 2 (also from ref. 1). The figure reveals that very few meteorites approach the earth head-on. More of them approach at about $\pm 90^{\circ}$ to the direct earth's motion, the largest number approaching from behind. Although the greatest number of meteorites approach the earth from behind, the forward velocity of the earth is of the same order as that of the meteorites themselves and, as a result, the hourly rate at which meteors are observed is greatest at sunrise. However, the large influx from the directions at $\pm 90^{\circ}$ to the direction of the earth also exerts a strong influence so that the diurnal variation shows strong peaks a few hours before and after sunrise. This effect is indicated in figure 3 (adapted from ref. 2).

There are seasonal shifts as well as daily variation in the meteor statistics and figure 4 (adapted from ref. 2) indicates that the time of daily maximum varies about 6 a.m. It occurs later in spring and earlier in winter. The range is about ± 2 hours. The mean hourly rate is also seasonally influenced and figure 5 indicates a lessening during the spring and a marked increase in the fall. The minimum is about 50 percent of the average and the maximum, about 50 percent greater than the average.

Perhaps the most significant single piece of data that can be measured on the motion of meteorite particles is the velocity. If the meteorite is a member of the solar system, its velocity limits are clearly defined. At the earth's distance from the sun, in an extremely elongated orbit, the maximum particle heliocentric velocity that could be reached exceeds the earth's velocity of 29.8 kilometers per second by a factor of $\sqrt{2}$ or a velocity of 42.1 kilometers per second. The vector sum which yields the geocentric velocity then ranges over the limits of 12.3 to 71.9 kilometers per second. If the effect of the earth's gravitational field is added, the upper limit may be increased to 72.6 and a lower limit established as that velocity attained by a particle initially not in motion with respect to the earth but attracted by it. Such a lower limit is 11.2 kilometers per second. Millman has developed a velocity histogram for 10,933 meteorites, the greater number of which were sporadics. His results are summarized in figure 6. The distribution is bimodal and has peaks in the range of 37 to 62 kilometers per second. Only 0.3 percent of the data appear to have velocities in excess of the maximum geocentric velocity.

Meteor trails show an influence of velocity on the altitude range over which they appear and disappear. At velocities near the lower limit, trails appear approximately over a range of altitude from 75 to 100 kilometers and disappear over a range of 45 to 75 kilometers. At velocities near the upper limit, meteors appear over the range 100 to 120 kilometers and disappear over the range 70 to 100 kilometers.

Number and Mass Distribution

It has been observed that over the range of meteors of visual magnitude 0 to 10 that the relationship of magnitude to number per magnitude for the whole earth is of the form

$$N = \text{Constant} \times 10^{0.4m}$$

that is, for each increase in magnitude m, the number increases by the factor 2.51. Current estimates of the constants vary. Watson in reference 3 suggests the relationship

$$N = 0.45 \times 10^{6} \times 10^{0.4m}$$

whereas Whipple in reference 4 suggests

$$N = 1.40 \times 10^{6} \times 10^{0.4m}$$

which is larger by a factor of three. The quantity N is the total number per day striking the earth's atmosphere and is obtained by prorating the estimated volume contained within the field of view of the observer. Since meteor trails are of finite length, proper consideration must be given to the overlap of those trails that partially enter the field of view. Further corrections to magnitude must be made for photographically observed meteors because of the different spectral sensitivity of the human eye and the photographic emulsions. These estimates are plotted in figure 7.

The most uncertain part of the reduction of meteor data concerns the establishment of the relationship between meteor mass and intensity or visual magnitude. By definition the intensity I

$$I = 10^{0.4m}$$

The intensity can be developed from the deceleration process if it is assumed that the light output is proportional to the kinetic energy of the ablated meteorite materials deposited in the wake.

The proportionality factor is recognized to be a function of the meteorite velocity. The analysis yields the relationship that the intensity I

$$I \approx (\mathrm{Mass})(\mathrm{Velocity})^{n}$$

or

$$\mathrm{Mass} = (\mathrm{Constant})(\mathrm{Velocity})^{-n}10^{0.4m}$$

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where n is any number and m denotes the magnitude.

More recent evaluations of this relationship can be inferred from results by Watson and Whipple. Watson's results are obtained from reference 3 and are equivalent to

$$M = 0.250 \times 10^{-0.4m} \text{ grams}$$

where M denotes the mass. Whipple's results are obtained from reference 4 and are equivalent to

$$M = 25.0 \times 10^{-0.4m} \text{ grams}$$

The relationships are shown in figure 8.

The choice of the factor $10^{0.4}$ in the ratio of number of meteorites per magnitude when combined with the mass-magnitude relationship yields the fact that the total accumulation of mass per magnitude is constant. Watson's results yield 1.1×10^{2} kilograms per day for the whole earth whereas Whipple's results yield 3.5×10^{5} kilograms per day. Elimination of visual magnitude between the number and mass estimates yields the number mass relationship given in figure 9.

Composition of Meteors

The composition of the meteorites can be obtained from two sources, that is, chemical analysis of those that are large enough to reach the ground and from photographs of spectra of meteor trails. The composition of the meteorites that are found places them into two classes although intermediate compositions are found. These two classes are the irons (containing essentially iron and nickel) and the stones (containing the whole spectrum of elements found in the earth's crust). Table I adapted from Watson (ref. 3) compares the composition of the irons and stones with the observance of the elements found in the earth's crust.

The spectra of meteor trails have been analyzed by P. W. Millman and from more than 120 spectra of meteors in the magnitude range of 0 to 9. Table II, adapted from reference 3, indicates the chemical elements found in the spectra. Whether an element exists in an excited state would appear to be a function of the velocity. The greater the velocity, the more excited the state. Of particular interest is the observation that many of the spectra indicate calcium or calcium ions; this phenomenon suggests a greater influx of stony particles.

SHOWER METEORS

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The more spectacular aspect of meteor influx is the meteor showers. These annually occurring events indicate that great streams of debris are in definite orbit about the sun and that the earth crosses these each year, some at two points of their orbits. Since the particles are in definite orbits they appear to have well-defined radiants from which their names are derived and well-defined velocities. Ranges in velocity of a given stream may vary over a range of several kilometers per second and radiants may be dispersed in a number of groups. It is now accepted that shower meteorites are of cometary origin and all the major showers have been correlated with known comets through their orbits. It is conceded that these showers which have a fairly uniform annual influx correspond to old comets for which the longer length of time has permitted the debris to be uniformly scattered along the trajectory. These showers which have indicated periodic variations in strength correspond to those for which the material is still concentrated in a dense core.

Although showers provide a more spectacular display and can increase the daily total rate by as much as a factor of 10, they constitute only a fraction of the total mass influx. Lovell in reference 1 estimates all showers to input 130,400 kilograms per year to the earth and at the same time estimates a total of 485,000 kilograms for the sporadics. It must be mentioned that later estimates of total meteoritic mass influx are greatly in excess of this figure; however, the ratios may be of greater significance.

Estimates of the spatial extent of the orbits of showers based on the earth's motion during their direction indicate width of streams of from 0.5×10^7 to 4.0×10^7 kilometers and density of material in orbit at 1.4×10^{12} to 15×10^{12} kilograms per cubic kilometer.

An interesting discovery of the radio observations has been the identification of the daytime showers which are fully as significant in rate and total influx of mass as the nighttime showers. Identification of daytime and nighttime showers resulting from the same stream has been accomplished. Such streams belong to orbits of such low inclination to the ecliptic that they would be intercepted twice by the earth.

A summary of the major showers is given in table III.

LARGE-SCALE METEORITES

It has been estimated that about 2,000 separate falls of large meteorites occur per year over the whole earth. Their total mass has been estimated to be about 200 tons. The largest known single meteorite weighs 60 tons. At least 12 large craters found on earth have been established to be of meteoritic origin. Those particles found at the craters have generally been metallic or metallic stones. These craters, for the most part, have been found in dry desert areas; this fact may account for their state of preservation. It is possible that the many craters produced by stones have been concealed by the similar character of the earth's crust or have been eroded by the atmosphere.

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The largest identified crater is at Barringer, Arizona. A single large mass fell and produced a crater 1,200 meters in diameter. Since 1950 strong suspicion has centered on a lake in Northern Quebec which is almost a perfect circle, 3,400 meters in diameter. In 1908 and 1947, falls have been observed in Russia. The fall of 1908 was estimated at a few hundred tons and produced damage over a range of 30 kilometers. The second fall was considerably smaller (several tons) and its range of damage was 5 kilometers.

DIRECT MEASUREMENTS OF METEORITES

The first observations of meteoritic impacts in vehicles at high altitudes is credited to J. L. Bohn (ref. 5) who had installed sensitive microphones on the skin of V-2 rockets that were fired from White Sands, N.M. Since these flights various sensing devices have been placed aboard sounding rockets, satellites, and space probes. There would seem to be a crude separation of the data if they are presented in the three categories of vehicles on which they were obtained. This presentation might equally well be interpreted as an altitude range of measurements. All the data to be reported are summarized in table IV.

Sounding Rocket Measurements

The first direct measurement of meteoritic impacts is credited to J. L. Bohn and F. H. Nadig during the V-2 flight at White Sands, N.M.

These measurements were made by ultrasonic microphones that had been attached to the vehicle surface and recorded the vibrations induced by impacts on the vehicle surface. These tests have not been reported in detail but are mentioned in reference 5. Sixty-six impacts were recorded during the 210 seconds that the vehicle was in the altitude range from 35 to 135 kilometers. The date of firing was December 8, 1949.

Berg and Meredith in reference 6 report on the flight of an Aerobee at White Sands, N.M. on November 17, 1955, the purpose of which was to measure direct impact of meteorites. Two sensors were flown and each sensor consisted of a frustum of a Lucite cone, the base of which was 75 square centimeters and was covered with an 8×10^{-6} centimeters thick layer of aluminum. The other flat surface was adjacent to a photomultiplier tube which recorded the light emitted by meteorite impact on the aluminum coating which was placed parallel to and close to the surface of the rocket. It was estimated that the device was sensitive enough to detect an impacting meteorite of energy 0.005 erg. Such an energy corresponds to an iron meteorite of 1-micron diameter and a velocity of 0.5 kilometer per second. The mass sensitivity could be 1.1×10^{-15} grams if a meteorite velocity of 30 kilometers per second is assumed.

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The vehicle trajectory reached an altitude of 103 kilometers, the zenith angle was less than 38° from take-off to reentry at 225 seconds at which time the vehicle tipped over to a zenith angle of 170°. Vehicle roll period was 6 seconds. Only one sensor was operative and recorded a total of 114 impacts during the period the vehicle was above 65 kilometers. Above 85 kilometers 101 impacts were recorded at a fairly uniform rate; no influence of vehicle roll is indicated. Certain observations are significant. The impact data were symmetrical about the trajectory, that is, uniform above 85 kilometers and tapering off at 65 kilometers, both in ascent and descent. During the reentry phase when the rocket tipped through a horizontal position, impacts were recorded only when the detector looked up. This flight was flown during the time of the Leonid shower; however, it should be observed that this is a periodic shower and in 1955 should not have been associated with any substantial increase in total activity.

Dubin in reference 7 reports the flight on July 16, 1957 of Aerobee no. 80 which was instrumented with skin microphones for recording impacts on a sensitive area of 0.5 m^2. The instrument had an impact momentum sensitivity of 2×10^{-3} gram-centimeters per second, or at an assumed velocity of 30 kilometers per second, a mass sensititivy of 7×10^{-10} grams. The flight reached an altitude of 130 kilometers and was above 90 kilometers from 92 seconds to 275 seconds and above 60 kilometers from 60 seconds to 300 seconds. Between 60 and

90 kilometers, 11 impacts were recorded on ascent and 6 on descent. Between 90 kilometers and the peak of 130 kilometers, 18 were recorded on ascent and 7 on descent.

A similar flight was made on October 16, 1957 with a more sensitive instrument which had a momentum sensitivity of 5×10^{-4} gram-centimeters per second or a mass sensitivity of 1.6×10^{-10}. It recorded an impact rate of 6.4×10^{-1} per second per square meter.

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J. F. Lovering in reference 8 reports a rocket flight made at Woomera, Australia with a Long Tom missile aboard which was a duplicate of the instrumentation used by Berg and Meredith. (See ref. 6.) The flight reached an altitude of 135 kilometers. The total time of flight was 495 seconds. It reached 53 kilometers in 50 seconds and spent 210 seconds above 85 kilometers. No counts were recorded although checks aboard the missile indicated all instrumentation was operating. Had the same rate of influx measured by Berg and Meredith applied, 276 hits on 82 square centimeters should have occurred in 210 seconds. A statistical analysis of the data reveals that, with confidence limits of 0.95, 0.99, and 0.999, the respective upper bounds are compatible with impact rates of 2.1, 3.1, and 4.2 per meter^2-second, respectively.

On May 27, 1958, an attempt was made to place a Vanguard (SLV-1) payload in orbit. The vehicle failed to orbit but did carry its instrument package to an extreme altitude of slightly less than 2,500 kilometers. The payload, a 20-inch sphere, separated from the third stage at 700 kilometers and reached the extreme altitude 590 seconds later. A description of the experiment is given by LaGow, Schaefer, and Schaffert in reference 9. The instrumentation consisted of lead zirconate disk microphones attached to the surface so that the entire surface was sensitive to impact. The most sensitive area near the microphones was capable of responding to a momentum of 1.7×10^{-3} gram-centimeters per second but the average over the surface was less and equal to 5.9×10^{-3} gram-centimeters per second. These values correspond at an impact velocity of 30 kilometers per second to masses of 6×10^{-8} grams and 2×10^{-8} grams. A total of 17 counts was recorded of which six were recorded during a short period of about 6 seconds.

Satellite Measurements

Rocket-launched satellites have made it possible to obtain significant direct measurements of meteorites by virtue of the fact that the time of data collection over that of sounding rockets is increased manyfold. Furthermore, the instrumentation is capable of greater sensitivity than either photographic or radio observations and therefore has extended our knowledge of the distribution of mass of meteoritic particles into the micrometeorite or cosmic dust range.

The first American satellite Explorer I (1958 Alpha) launched on January 31, 1958 carried aboard two types of instrumentation for the detection of micrometeorites. One was an exposed surface area of 0.23 meter^2-second upon which impacts were registered by an ultrasonic microphone, and the other was an assembly of 12 wire grid gages. Each grid consists of two layers of 17-micron wire wound on a card 1 centimeter $\times$ 1 centimeter. Sensitivity of the microphone gage was measured to be 2.5×10^{-3} gram-centimeters per second for momentum or at an assumed average velocity of 30 kilometers per second to be 8.0×10^{-10} grams. Sensitivity for the wire grids has been established at about 10-micron diameter for particles at meteoritic velocities. A complete report of the data obtained is given in reference 10. A complete description of the instruments and their calibration is given in reference 11.

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Data were recorded over an 11-day period from February 1 to February 11, 1958, along an orbit with apogee of 2,555 kilometers, perigee of 374 kilometers, and period of 115 minutes. A total of 145 impacts was recorded during 78,750 seconds of operation in the microphone impact recorder. Eight additional apparent impacts recorded on launch were discarded. The impact rate for the 0.23-meter^2 surface of all particles to 8.0×10^{-10} grams is 8×10^{-3} impacts per meter^2-second.

An analysis of the data on the basis of impacts as a function of local time indicates a diurnal variation that corresponds to a greater impact rate before noon. The ratio of morning to evening impact rates is about 3 to 1. During five successive orbits or about 8 hours of a total of 12 days, the satellite experienced a shower flux whose rate of impact was 20 times that of the average rate experienced during the 12 days of operation.

None or at most one hit was recorded on the wire gage during the period February 1 to April 14.

On March 26, 1958, Explorer III (1958 gamma) was launched into an orbit of apogee 2,801 kilometers, perigee 188 kilometers, and period of 116 minutes. It carried aboard 12 wire gages of the type used on Explorer I for the measurement of micrometeorites. It does not appear to be worthwhile to attempt to reduce the events recorded by these devices to average rates but the following sequence of events recorded in reference 12 is worth noting:

Date	Event
May 7	Two grids failed.
May 8	Channel 5 of low-power transmitter failed.
May 9	Modulation of low-power transmitter failed.
May 10	Command receiver failed to respond.
May 11	High-power transmitter failed.
May 12	Low-power transmitter failed.

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The inference is that these two separate transmitters with separate power supplies were destroyed by impacts from the Eta Aquarides shower which reaches its peak about May 5. It must be remarked that both Explorer I and Vanguard I operated successfully through this time period.

In reference 13, H. E. LaGow and W. M. Alexander made a preliminary report on measurements made with Vanguard III. This satellite (1958 Epsilon) was launched September 18, 1959 and had initially an apogee of 3,748 kilometers, a perigee of 513 kilometers, and a period of 130 minutes. The entire surface of the 20-inch-diameter sphere was considered sensitive to the impacts which were recorded by microphones cemented to the skin. Except for a small region over each microphone the momentum sensitivity averaged 0.9×10^{-2} to 1.2×10^{-2} gram-centimeters per second at which an assumed velocity of 30 kilometers per second corresponds to a mass of 3.3×10^{-9} grams. During the period from September 18 to October 9 a total of more than 1,500 impacts was recorded. About 500 of these counts were subsequently found to be false counts triggered by interference from the interrogation circuits. A total of 990 counts has tentatively been established for the 22-day period. If an average cross-sectional area of 0.2 meter^2 is assumed, this value corresponds to a flux of 2.6×10^{-3} per meter^2-second. If it is assumed that the flux is isotropic and at the average altitude of the satellite 0.2 of the flux is shadowed by the earth, the corrected isotropic omnidirectional flux is 3.25×10^{-3} per meter^2-second. Over the 22-day period this rate decreased to as low as 1.45×10^{-3} per meter^2-second and reached a peak as high as 6.5×10^{-3} per meter^2-second.

Explorer VII (1959 Iota) launched on October 13, 1959 with an apogee of 1,091 kilometers, a perigee of 556 kilometers, and a period of 101 minutes carried a micrometeorite detector. The detector sensitive to particles about 10 microns in diameter consisted of a cadmium sulphide photosensitive conductor covered with an opaque film which is punctured on impact and admits sunlight. In references 14 and 15 it is reported that only one hit had been recorded as of February 13, 1960 and that one occurred on launch.

Explorer VIII (1960 Xi 1) was launched into orbit on November 3, 1960 with an apogee of 2,277 kilometers, a perigee of 403 kilometers, and a period of 113 minutes. Two types of detectors were carried aboard: one, an aluminum-covered photomultiplier tube sensitive to particles of mass as small as 10^{-13} grams at velocities of 10 kilometers per second; the other, a sounding board and microphone. Two sounding-board installations were used and the counting was done at three sensitivity levels, which corresponded to masses of 10^{-9}, 10^{-8}, and 10^{-7} grams. The reduced data for this flight are available in reference 16, and are presented in figure 10.

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Russian data obtained from satellites are only incompletely recorded in the literature. In reference 17 a summary of results obtained from Sputnik III (1958 Delta) is reported. Four detectors of the ballistic piezo-electric type having a total sensitive area of 3,410 square centimeters were installed on the satellite. A sensitivity of 10^{-9} grams was obtained by calibration at low velocities and by assuming an average meteoritic velocity of 40 kilometers per second. Preliminary data indicated an average impact rate of 1.7×10^{-3} impacts per meter^2-second. Although no implications of an altitude variation are intended, it is reported that at times of large increase in impact frequency, rates of 22 impacts per meter^2-second were recorded in the altitude range of 1,700 to 1,800 kilometers; 10, in altitude range of 1,300 to 1,500 kilometers; and 9 in altitude range of 1,500 to 5,000 kilometers.

In a more recent paper (ref. 18) the data from Sputnik III are reported as follows:

Date launched	Mean approximate mass of registered micrometeorites in grams if $V = 4 \times 10^6$ cm/sec	Intensity of flux of micrometeorites, m^2sec^{-1}	Approximate mass of micrometeorite matter in tons for whole globe in 24 hours
May 15, 1958			
May 15, 1958	2×10^{-8}	5 to 10	5 to 10×10^6
May 16-17, 1958	8×10^{-9} to 30×10^{-9}	5×10^{-3}	5×10^3
May 19-26, 1958		$< 10^{-4}$	$< 10^2$

Space Probe Measurements

Both American and Russian space probes have had micrometeorite sensing instrumentation aboard. The relatively short flight times, as compared with satellites, makes them less desirable vehicles for obtaining statistically reliable samples. They do, however, provide some information at great distances from the earth.

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The data obtained from Pioneer I flights are reported in reference 19. Instrumentation similar to that used on the Explorer satellites and developed by the U.S. Air Force Cambridge Research Center was employed. The sensitive surface was a 5-inch by 12-inch curved plate (0.0381 square meter) with a 14.5-inch radius and acoustically isolated from the payload shell. A microphone and amplifier circuit operating at 90 kilocycles was used to record the impacts. Two levels of sensitivity were established in the amplifier. Calibration indicated the following thresholds of sensitivity:

Sensitivity at microphone	Average sensitivity over diaphragm	Channel
6×10^{-5} gm-cm/sec	15×10^{-5}	Sensitive
250×10^{-5}	530×10^{-5}	Insensitive

At 30 kilometers per second the average mass sensitivities correspond to 5×10^{-11} grams and 176×10^{-11} grams.

A more detailed look at the data in reference 10 indicates that a total of 17 impacts were recorded in a telemetry time of 1.1×10^5 seconds out of a total of 1.6×10^5 seconds during which time the vehicle reached a distance 19 earth radii from its center. One impact that occurred at a distance 5.7 earth radii from the earth's center was of sufficient intensity to record on both high and low sensitivity channels.

In addition to the total of 17 recorded hits, seven additional impulses were recorded at 18 earth radii from the center of the earth during a period of 240 seconds and were excluded because of the peculiar nature of the recorded signal. The average impact rate corresponds to 4×10^{-3} per meter^2-second. The data indicate, however, a tendency for the impact rate to decrease with increasing distance from the earth.

Russian data from cosmic rockets have been sketchily presented in the following form in reference 17:

Means of exploration	Date launched	Mean approximate mass of registered micrometeorites in grams if $V = 4 \times 10^6$ cm/sec	Intensity of flux of micrometeorites, $m^2 sec^{-1}$	Approximate mass of micrometeorite matter in tons for whole globe in 24 hours
1 cosmic rocket	Jan. 2, 1959	10^{-9}	$< 2 \times 10^{-4}$	< 10
2 cosmic rocket	Sept. 12, 1958	10^{-8}	$\approx 2 \times 10^{-4}$	$\approx 10^2$

THE METEORITIC HAZARD IN NEAR SPACE

Whipple's Estimate

The assessment of the hazard to flight beyond the near atmosphere has been made by F. L. Whipple in reference 4. The observational basis of the study rests on the meteor photographic program of the Harvard Observatory. The results of the study are summarized in table V which is adapted from reference 4. The eighth column has been referred to a cross-sectional area of 1 meter^2 instead of the area used in reference 4, and the earth-shielding factor has not been included. The significant assumptions on which the analysis rests are:

1. A meteor of visual magnitude 0 corresponds to a meteoroid with a mass of 25 grams.

2. Mass decreases in the ratio of $10^{0.4}$ (2.514) per step in visual magnitude.

3. The apparent density of the larger size meteorite is 0.05, that is, porous fragments. This value is adjusted for meteorites of visual magnitude 23 or greater in order to maintain the size of meteorite at the limit imposed by the balance between the sun's gravitational force and its light pressure.

4. The velocity of meteoroids is 28 kilometers per second and is reduced for the less bright meteorites to 15 kilometers per second which is just above the minimum limiting velocity.

5. The accumulated number for the whole earth per day is 2×10^8 grams to the limit of the naked eye observation, visual magnitude 5. For greater magnitudes the total accumulated number up to a given magnitude increases in the ratio $10^{0.4}$ (2.514).

In figure 10 is shown a comparison of the mass frequency distribution law accepted by Whipple and the data of the direct measurements previously summarized in table IV but now reduced to omnidirectional flux. Also shown is the earlier estimate given in reference 3 by Watson.

Penetration Phenomena

Any estimate of the meteoritic hazard in space must rest on an estimate of the penetration of a given surface by a meteoroid particle. Whipple's estimate is based on the energy balance between the kinetic energy of the particle and the heat energy required to vaporize a crater of surface material of a given shape (that is, a cone with 60° apex angle). As such it is a simple theory in that it requires for the impacting particle only a knowledge of its kinetic energy. Much experimental evidence has been obtained on the penetrating capacity of simple geometrically shaped projectiles impacting into thick slabs. Most of the common materials have been used in these experiments and a large body of information exists over a velocity range which has an upper limit at about 12,000 feet per second. A few isolated data are available at higher velocities. As such, all empirically derived penetration equations suffer from the fact that they must be extrapolated into the range of meteoroid velocities. This difficulty is somewhat ameliorated by the study of Charters and Locke (ref. 20) whose data indicate that the ratio of impact velocity to sound velocity in the target is a significant parameter. Therefore penetration data obtained for impacts in lead targets for which the velocity of sound is 4,025 feet per second (1.22 kilometers per second) and for which considerable data exist at velocity ratios of 2 to 3 may be regarded as valid for impacts at much higher absolute velocities in aluminum and steel. A summary of the empirical penetration relationships developed by Huth, Thompson, and Van Valkenburg (ref. 21), Collins and Kinard (ref. 22), Charters and Locke (ref. 20) are given in figure 11 for steel projectiles in steel targets. Also shown are Whipple's estimates and those of Bjork (ref. 23) which are based on numerical solutions of the impact phenomena regarded as a compressible hydrodynamic phenomena.

If an average velocity of meteoritic impact of 30 kilometers per second is assumed, then the ratio of penetration to particle diameter covers a span of one-third to three times the estimates made by Whipple. The simplicity of Whipple's estimate being considered, it is in substantial agreement with the penetration law devised by Charters and Locke. It is difficult to accept the estimates that are on the high side because there does not appear to be sufficient energy available for them. The only estimate on the low side is that due to Bjork and it rests as yet on a few, although difficult, theoretical calculations.

Penetration Statistics

In figure 12 are summarized the average rates of penetration of aluminum surfaces proposed by Whipple. The average rates are substantially the same as those that would have been reduced from the penetration law of Charters and Locke if it is assumed that meteoroid particles had densities of the order of the material of the vehicle surface.

Of more interest to vehicle designers is the probability of impact on a single vehicle. If it is assumed that the probability of meteoroid
impact follows the law for the occurrence of rare events, which exhibits L
the characteristic that on the average the number of events is propor- 1
tional to the time of exposure, then the appropriate distribution for 9
occurrence of any number of independent events may be regarded as fol- 6
lowing a Poisson distribution. 3

If λ is the average rate of penetration and t the duration of exposure, then the probability P of n penetrations P_n is

$$P_n = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$$

The probability of no penetrations P_0 is

$$P_0 = e^{-\lambda t}$$

and the probability of at least one penetration is

$$P_1 = 1 - e^{-\lambda t}$$

For small values of λt the probability of at least one penetration is λt.

If use is made of the average rates of penetration given in figure 12, the probability of penetration of various thicknesses of aluminum sheet can be computed as a function of time of exposure. These results are given in figure 13.

CONCLUDING REMARKS

A brief survey is made of the general characteristics of the meteorite phenomena, that is, the temporal and spatial distribution of their number and direction, the meteoroid velocities, and their flux as a function of visual magnitude and mass. A comparison is made of the most recent direct satellite measurements of the meteoroid flux as a function of mass with that proposed by F. L. Whipple on the basis of radar and photographic observations. There is much scatter in the experimental results and the range is an order of magnitude above and below Whipple's estimate.

On the basis of Whipple's estimate of the meteoroid flux, penetration statistics which use a law of penetration based on energy considerations are obtained. This penetration law is in substantial agreement with that proposed by Charters and Locke based on their experimental results.

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The penetration statistics indicate that a vehicle whose cross-sectional area is of the order of 100 square feet and whose exposure period is of the order of 10 days has the expectation of 1 in 2, or better, of at least one penetration if its surface is aluminum and 0.1 inch thick or less.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., February 7, 1962.

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TABLE I.- COMPOSITION OF METEORITES

[From ref. 3]

Element	Type		Earth's crust, percent
	Iron, percent	Stones, percent	
Oxygen		36.3	49.4
Iron	90.8	24.1	4.7
Silicon		18.0	25.8
Magnesium		13.9	1.9
Sulfur	.04	1.8	.05
Calcium		1.7	3.4
Aluminum		1.5	7.5
Nickel	8.5	1.5	.02
Sodium		.7	2.6
Chromium	.01	.3	.03
Manganese		.26	.08
Potassium		.18	2.4
Phosphorus	.17	.14	.12
Cobalt	.59	.14	-----
Carbon	.03	-----	.09
Copper	.02	-----	.01

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TABLE II.- CHEMICAL ELEMENTS OBSERVED IN 44 METEOR SPECTRA

Element	Number of spectra
Iron	37
Calcium ion	33
Calcium	17
Manganese	9
Magnesium	7
Chromium	3
Magnesium ion	2
Silicon ion	2
Nickel	2
Aluminum	2
Sodium	1

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TABLE III.- MAJOR SHOWERS

Name	Days of maximum activity	Period, years	Velocity, km/sec
Perseids	Aug. 1 to 14	108	60.5
Leonids	Nov. 16 to 17	33	72.0
Lyrids	April 21	41.5	48.6
Andromedes	Nov. 23 to Dec. 6	6.6	16.0
Eta aquarides	May 4 to 6	11	60
Orionids	Oct. 20 to 23	16	66.5
Draconids	Oct. 10	6.6	23.3
Taurids	Nov. 3 to 10	3.4	37
Ursids	Dec. 22	13.5	37
Geminids	Dec. 12 to 13	1.7	36.4
Delta aquarides	July 28	2	43.0
Quadrantids*	Jan. 3	-----	44.1
Arietids*	May 29 to June 19	-----	37
Beta taurids*	June 24 to July 25	-----	31

*Daytime.

TABLE IV.- SUMMARY OF DIRECT MICROMETEORITE MEASUREMENTS

Vehicle	Date	Sensitive area, sq cm	Time of exposure, sec	Significance parameter (area × time)	Average impact rate, no./m^2-sec	Sensitivity momentum, gm-cm/sec	Sensitivity mass, gm
Sounding rocket measurements							
V-2 (no. 31)	Dec. 8, 1949	$\approx 10^4$	210	$\approx 2 \times 10^6$	6×10^{-1}		
Aerobee (no. 25)	Nov. 17, 1955	75	200	1.5×10^6	1.5×10^2		1×10^{-15}
Aerobee (no. 80)	July 16, 1957	5×10^3	240	1.2×10^6	2.3×10^{-1}	2×10^{-3}	7×10^{-10}
Aerobee	Oct. 16, 1957	5×10^3	≈ 100	5×10^5	6.4×10^{-1}	5×10^{-4}	$\approx 10^{-10}$
Long Tom	May 27, 1959	75	210	1.6×10^4	None		1×10^{-15}
Vanguard (SLV-1)	May 27, 1958	8×10^3	590	4.7×10^6	3.6×10^{-2}	5.9×10^{-3}	2×10^{-8}
Satellite measurements							
Explorer I	Feb. 1 to 11, 1958	2.3×10^3	7.88×10^4	1.8×10^8	8×10^{-3}	2.5×10^{-3}	8×10^{-10}
		1.1×10^1	6×10^6	6.6×10^7	0		$\approx 2 \times 10^{-9}$
Explorer III	Mar. 26, 1958	1.2×10^1	3.7×10^6	4.5×10^7	$\approx 4 \times 10^{-4}$		$\approx 2 \times 10^{-9}$
Vanguard III	Sept. 18, 1959	8×10^3	1.9×10^6	1.5×10^{10}	6.5×10^{-4}	1.0×10^{-2}	3.3×10^{-9}
Sputnik III	May 15, 1958	3.4×10^3	$\approx 10^8$	$\approx 10^{11}$	1.7×10^{-3}	1×10^{-1}	10^{-9}
Space probes							
Pioneer I	Oct. 10, 1958	3.8×10^2	1.1×10^5	4.2×10^7	4×10^{-3}	1.5×10^{-4}	5×10^{-11}
					(1 impact)	5.3×10^{-3}	1.76×10
Pioneer II	Nov. 8, 1958	3.8×10^2	1.2×10^2	4.6×10^4	6.1	1.5×10^{-4}	5×10^{-11}
1 Cosmic rocket	Jan. 2, 1959				$<2 \times 10^{-4}$		10^{-9}
2 Cosmic rocket	Sept. 12, 1959				$\approx 2 \times 10^{-4}$		10^{-8}

TABLE V.- DATA ON METEOROIDS AND THEIR PENETRATION PROBABILITIES

Meteor, visual magnitude	Mass, grams	Radius, microns	Velocity, km/sec	Kinetic energy, ergs	Penetration in aluminum, cm	Accumulated number striking whole earth per day	Accumulated number striking sphere of 1 meter^2 cross section per second
0	25.0	49,200	28	1.0×10^{14}	21.3		
1	9.95	36,200	28	3.98×10^{13}	15.7		
2	3.96	26,600	28	1.58×10^{13}	11.5		
3	1.58	19,600	28	6.31×10^{12}	8.48		
4	.628	14,400	28	2.51×10^{12}	6.24		
5	.250	10,600	28	1.00×10^{12}	4.59	2×10^{8}	1.82×10^{-11}
6	9.95×10^{-2}	7,800	28	3.98×10^{11}	3.38	5.84×10^{8}	5.30×10^{-11}
7	3.96×10^{-2}	5,740	28	1.58×10^{11}	2.48	1.47×10^{9}	1.335×10^{-10}
8	1.58×10^{-2}	4,220	27	5.87×10^{10}	1.79	3.69×10^{9}	3.35×10^{-10}
9	6.28×10^{-3}	3,110	26	2.17×10^{10}	1.28	9.26×10^{9}	8.41×10^{-10}
10	2.50×10^{-3}	2,290	25	7.97×10^{9}	.917	2.33×10^{10}	2.12×10^{-9}
11	9.95×10^{-4}	1,680	24	2.93×10^{9}	0.656	5.84×10^{10}	5.30×10^{-9}
12	3.96×10^{-4}	1,240	23	1.07×10^{9}	.469	1.47×10^{11}	1.335×10^{-8}
13	1.58×10^{-4}	910	22	3.89×10^{8}	.335	3.69×10^{11}	3.35×10^{-8}
14	6.28×10^{-5}	669	21	1.41×10^{8}	.238	9.26×10^{11}	8.41×10^{-8}
15	2.50×10^{-5}	492	20	5.10×10^{7}	.170	2.33×10^{12}	2.12×10^{-7}
16	9.95×10^{-6}	362	19	1.83×10^{7}	0.121	5.84×10^{12}	5.30×10^{-7}
17	3.96×10^{-6}	266	18	6.55×10^{6}	.0859	1.47×10^{13}	1.335×10^{-6}
18	1.58×10^{-6}	196	17	2.33×10^{6}	.0608	3.69×10^{13}	3.35×10^{-6}
19	6.28×10^{-7}	144	16	8.20×10^{5}	.0430	9.26×10^{13}	8.41×10^{-6}
20	2.50×10^{-7}	106	15	2.87×10^{5}	.0303	2.33×10^{14}	2.12×10^{-5}
21	9.95×10^{-8}	78.0	15	1.14×10^{5}	0.0223	5.84×10^{14}	5.30×10^{-5}
22	3.96×10^{-8}	57.4	15	4.55×10^{4}	.0164	1.47×10^{15}	1.335×10^{-4}
23	1.58×10^{-8}	*39.8	15	1.81×10^{4}	.0121	3.69×10^{15}	3.35×10^{-4}
24	6.28×10^{-9}	*25.1	15	7.21×10^{3}	.0084	9.26×10^{15}	8.41×10^{-4}
25	2.50×10^{-9}	*15.8	15	2.87×10^{3}	.00653	2.33×10^{16}	2.12×10^{-3}
26	9.95×10^{-10}	*10.0	15	1.14×10^{3}	0.00480	5.84×10^{16}	5.30×10^{-3}
27	3.96×10^{-10}	*6.30	15	4.55×10^{2}	.00353	1.47×10^{17}	1.335×10^{-2}
28	1.58×10^{-10}	*3.98	15	1.81×10^{2}	.00260	3.69×10^{17}	3.35×10^{-2}
29	6.28×10^{-11}	*2.51	15	7.21×10	.00191	9.26×10^{17}	8.41×10^{-2}
30	2.50×10^{-11}	*1.58	15	2.87×10	.00141	2.33×10^{18}	2.12×10^{-1}
31	9.95×10^{-12}	*1.00	15	1.14×10	.00103	5.84×10^{18}	5.30×10^{-1}

*Maximum radius permitted by solar light pressure.

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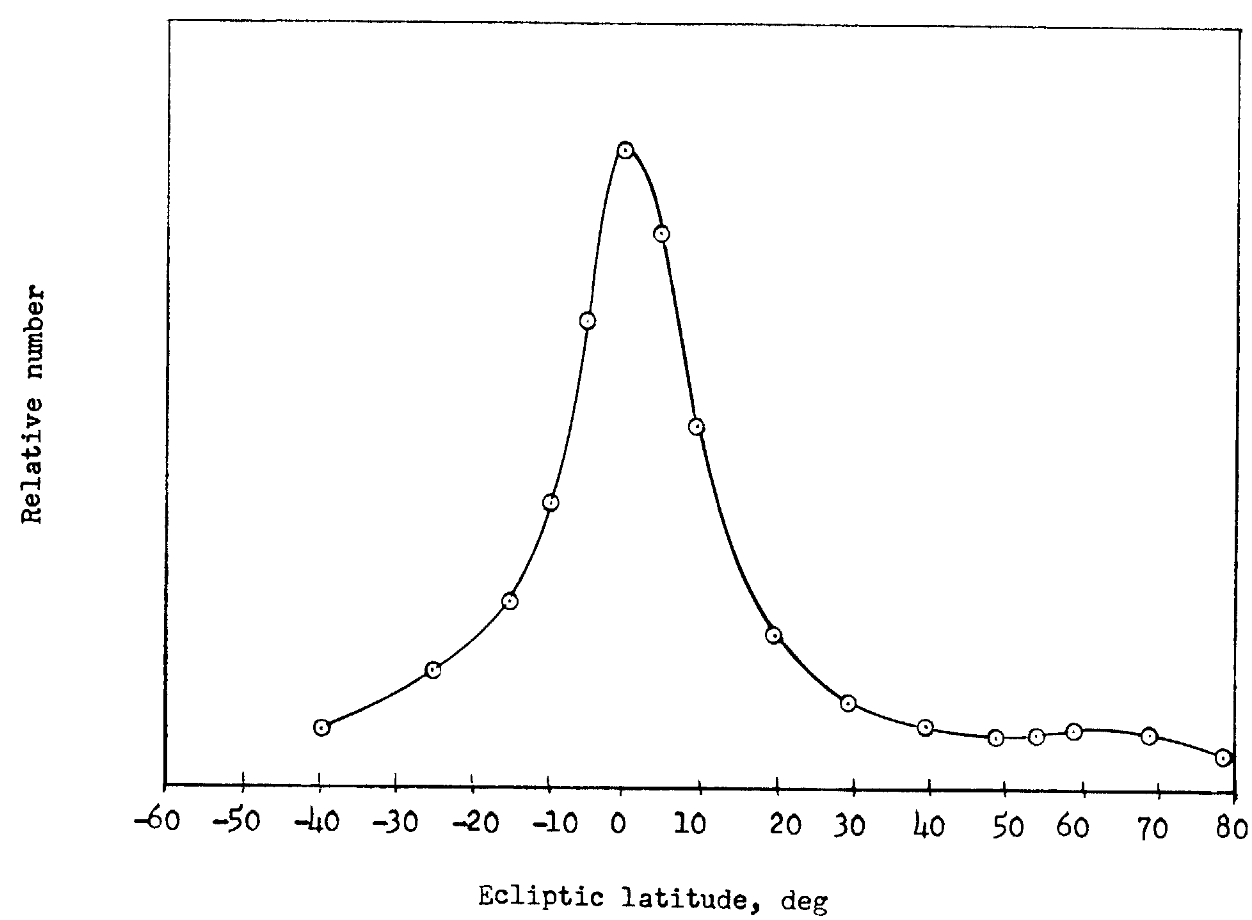

Figure 1.- Distribution of visual radiants of sporadic meteors in ecliptic latitude.

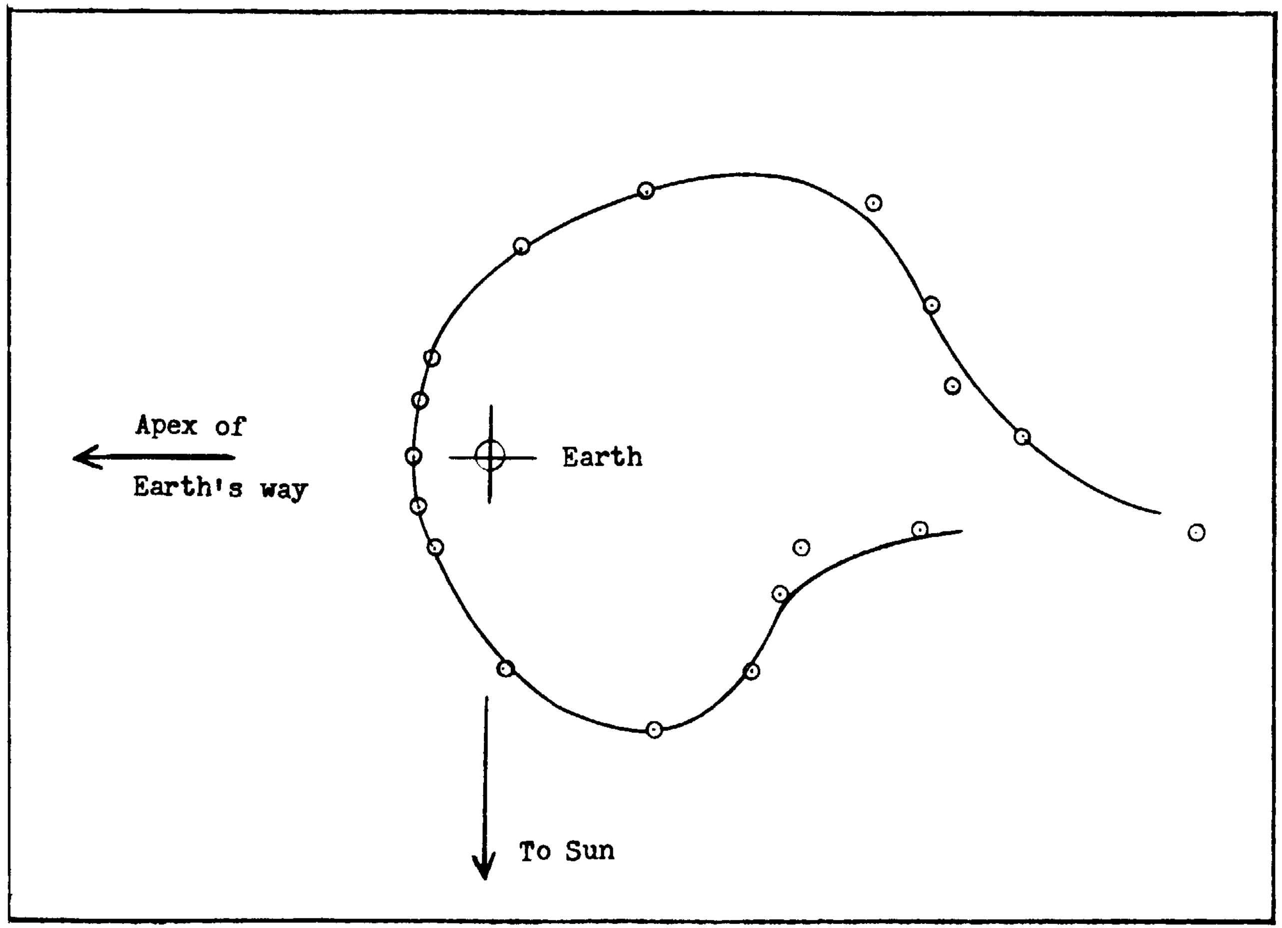

Figure 2.- Distribution of orbital directions of sporadic meteors.

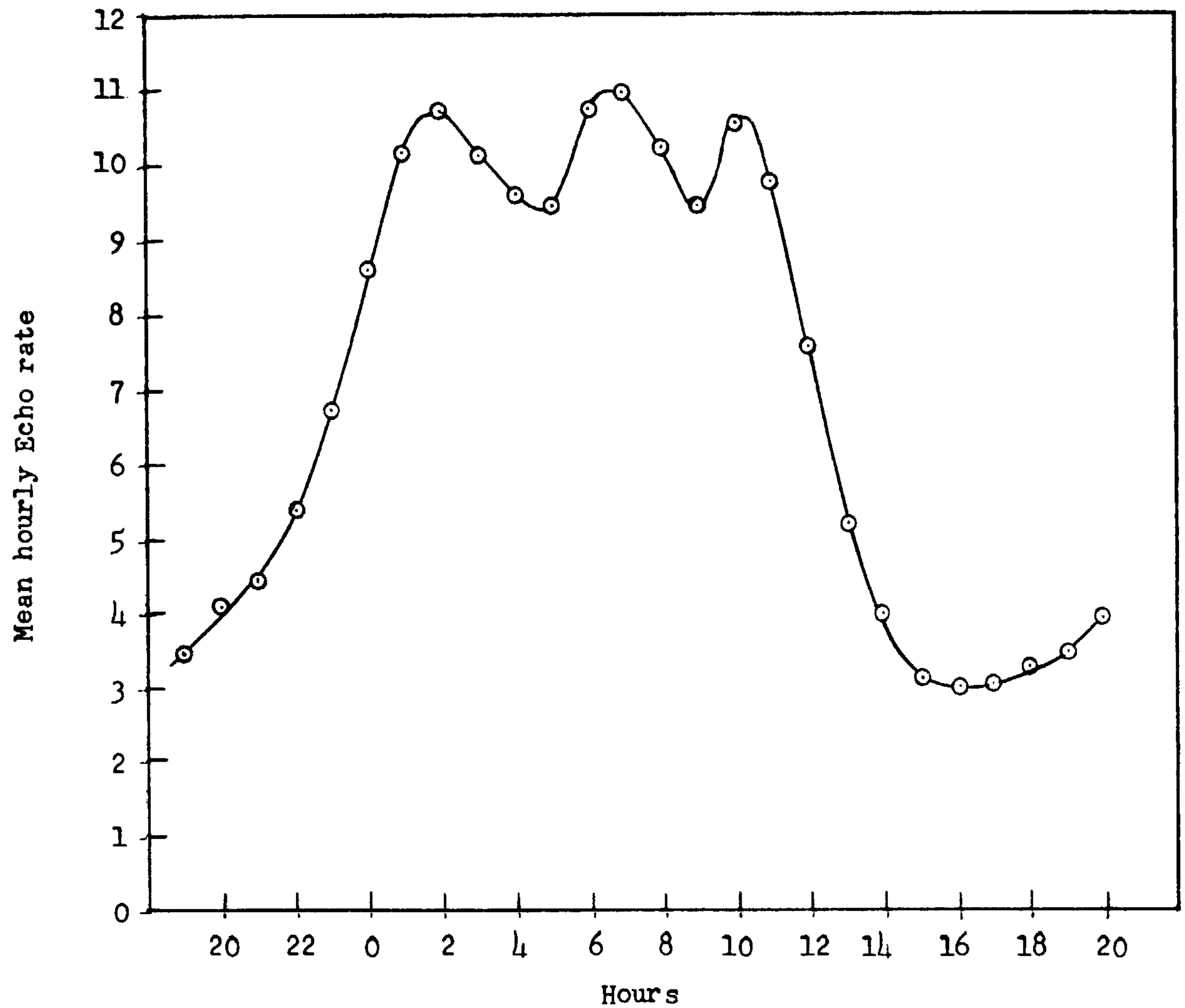

Figure 3.- Diurnal variation of sporadic meteors. (From ref. 2.)

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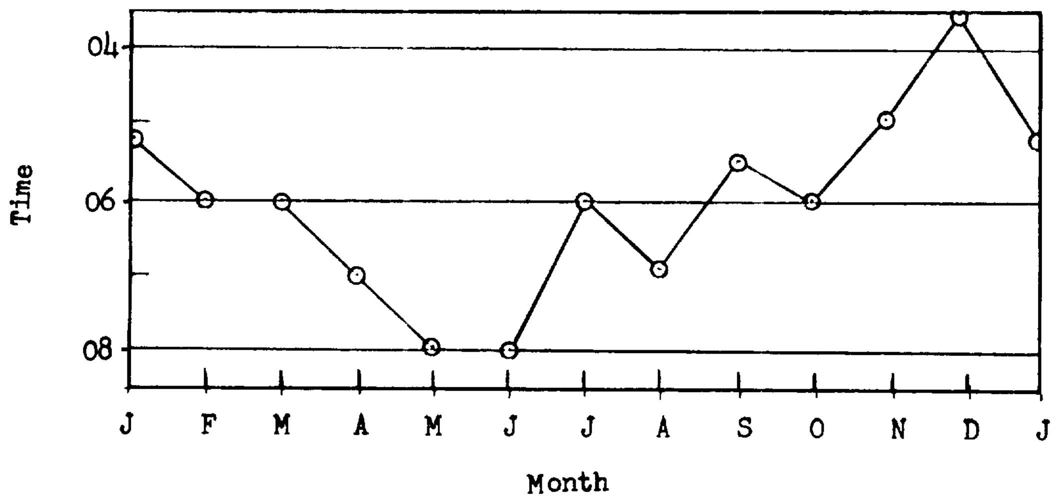

Figure 4.- Seasonal variation of the time of the daily maximum of sporadic meteor rate. (From ref. 2.)

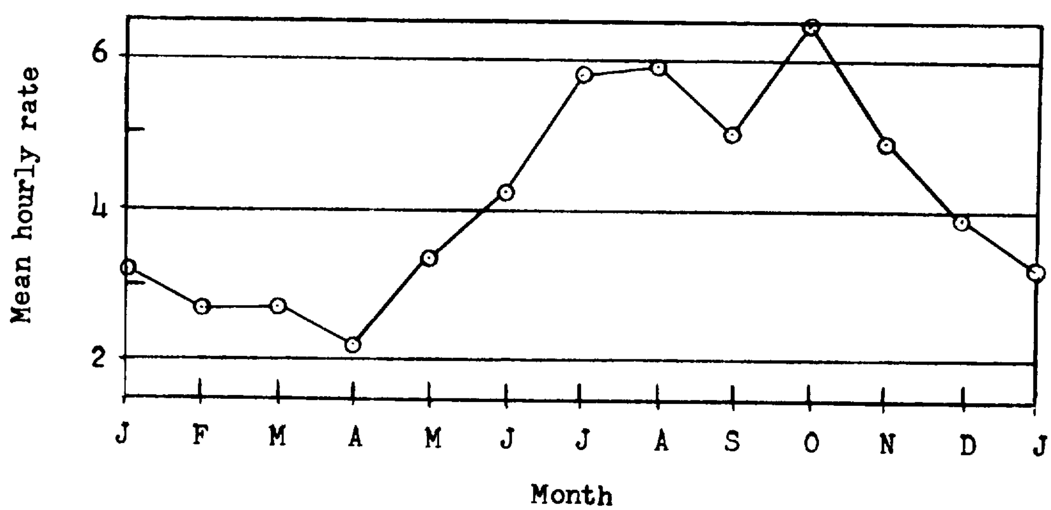

Figure 5.- Seasonal variation of the mean hourly rate.

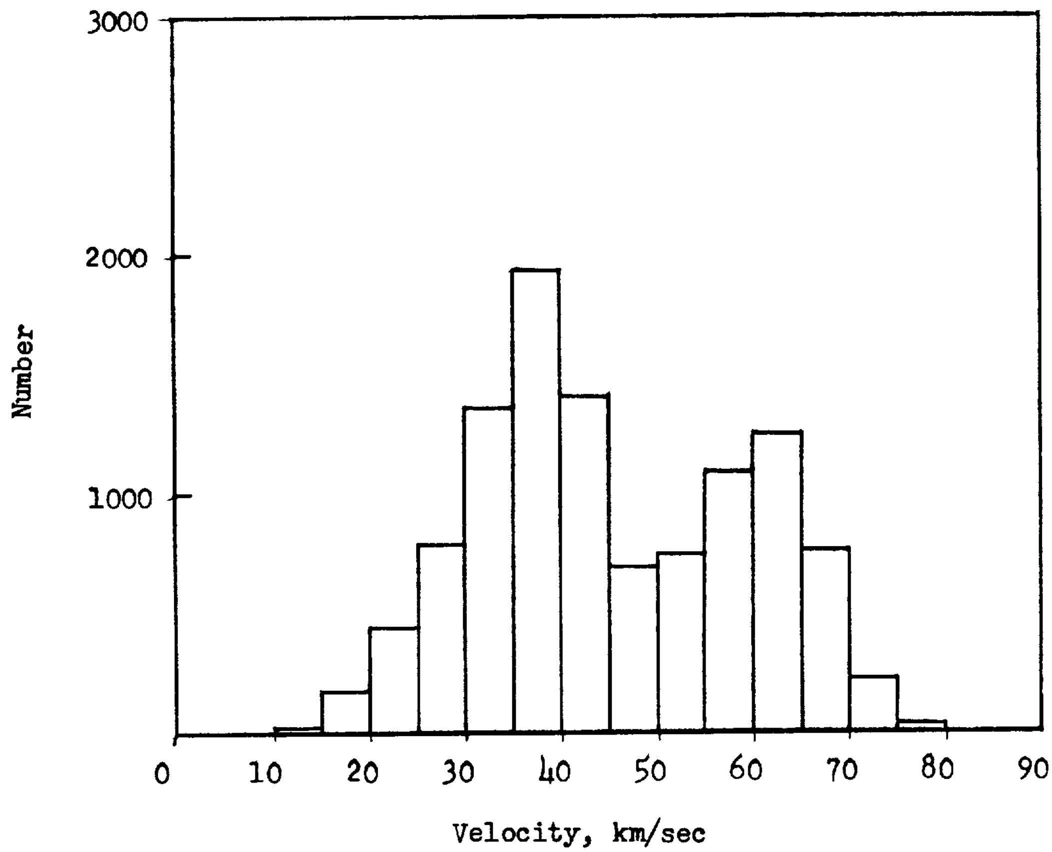

Figure 6.- Distribution of velocities of 10,933 sporadic meteorites.

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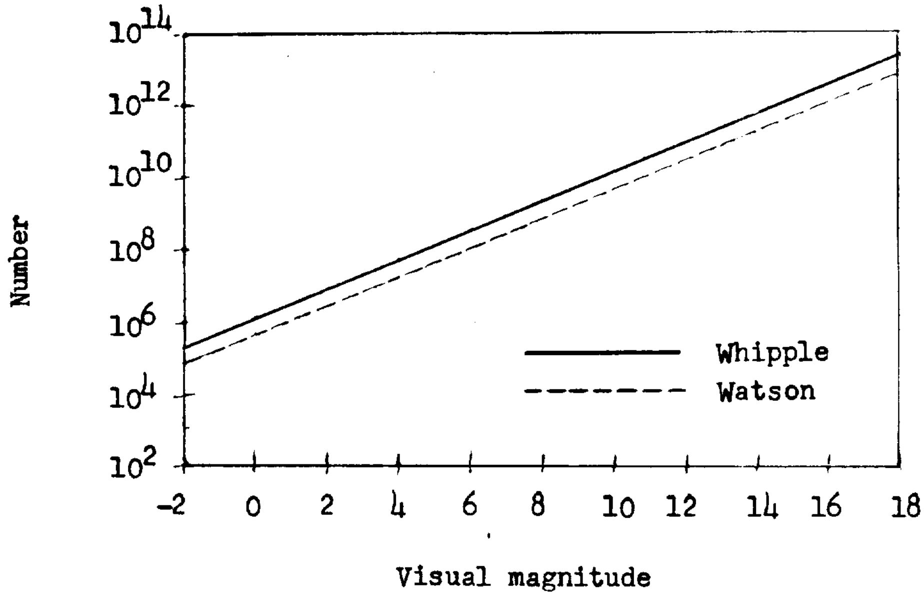

Figure 7.- Number of sporadic meteors per visual magnitude as a function of visual magnitude.

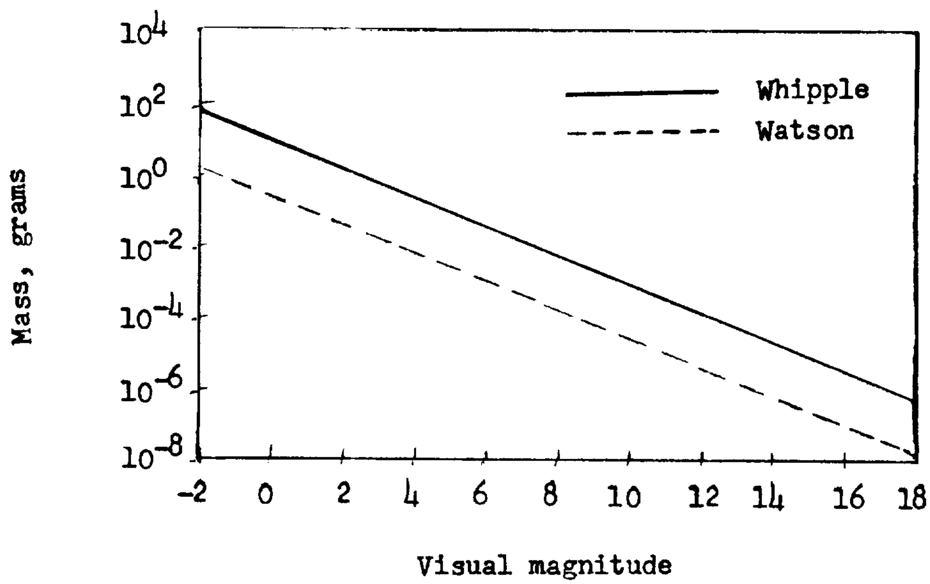

Figure 8.- Mass of a sporadic meteorite as a function of visual magnitude.

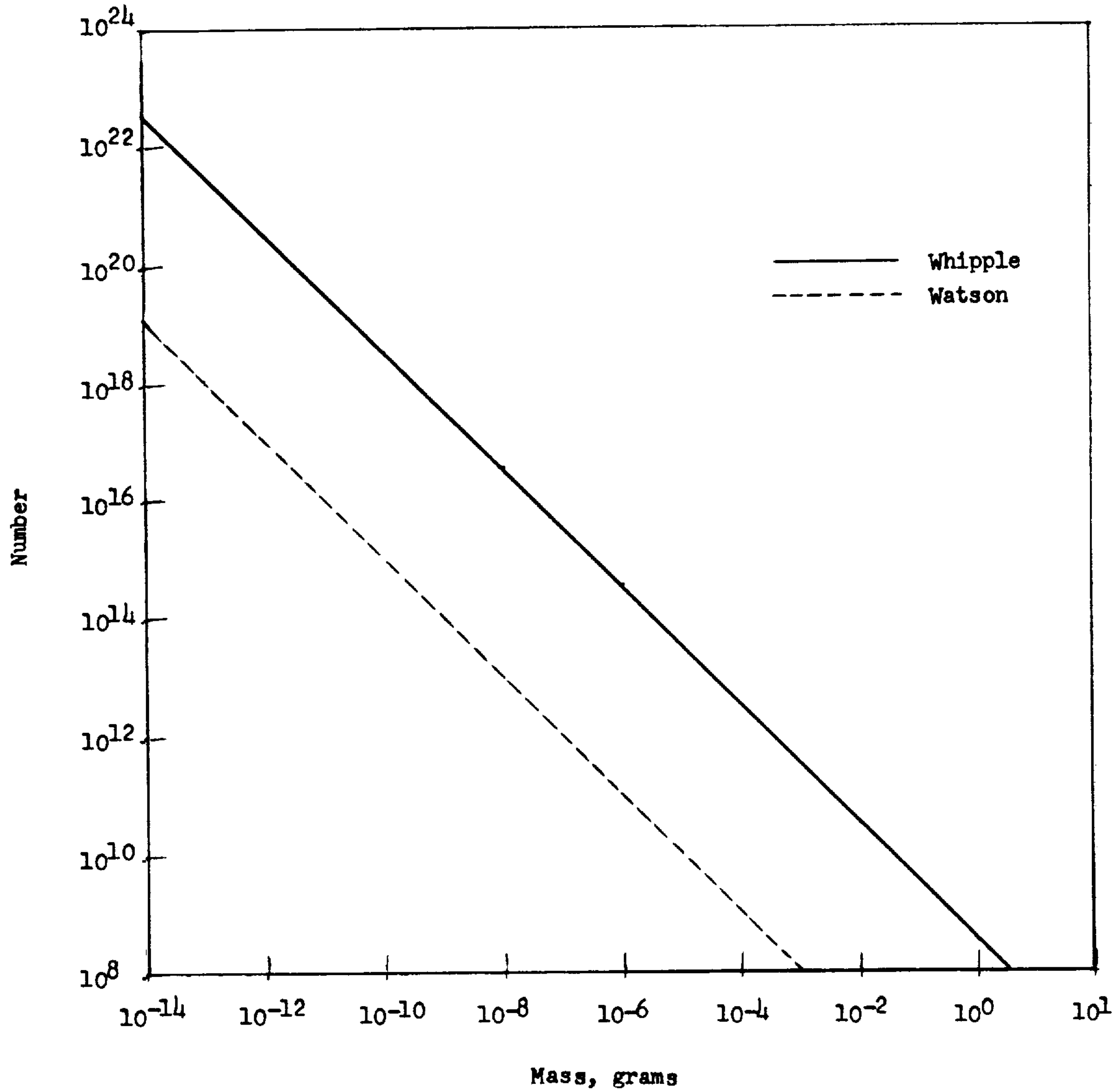

Figure 9.- Number of meteorites per visual magnitude striking whole earth per day as a function of mass.

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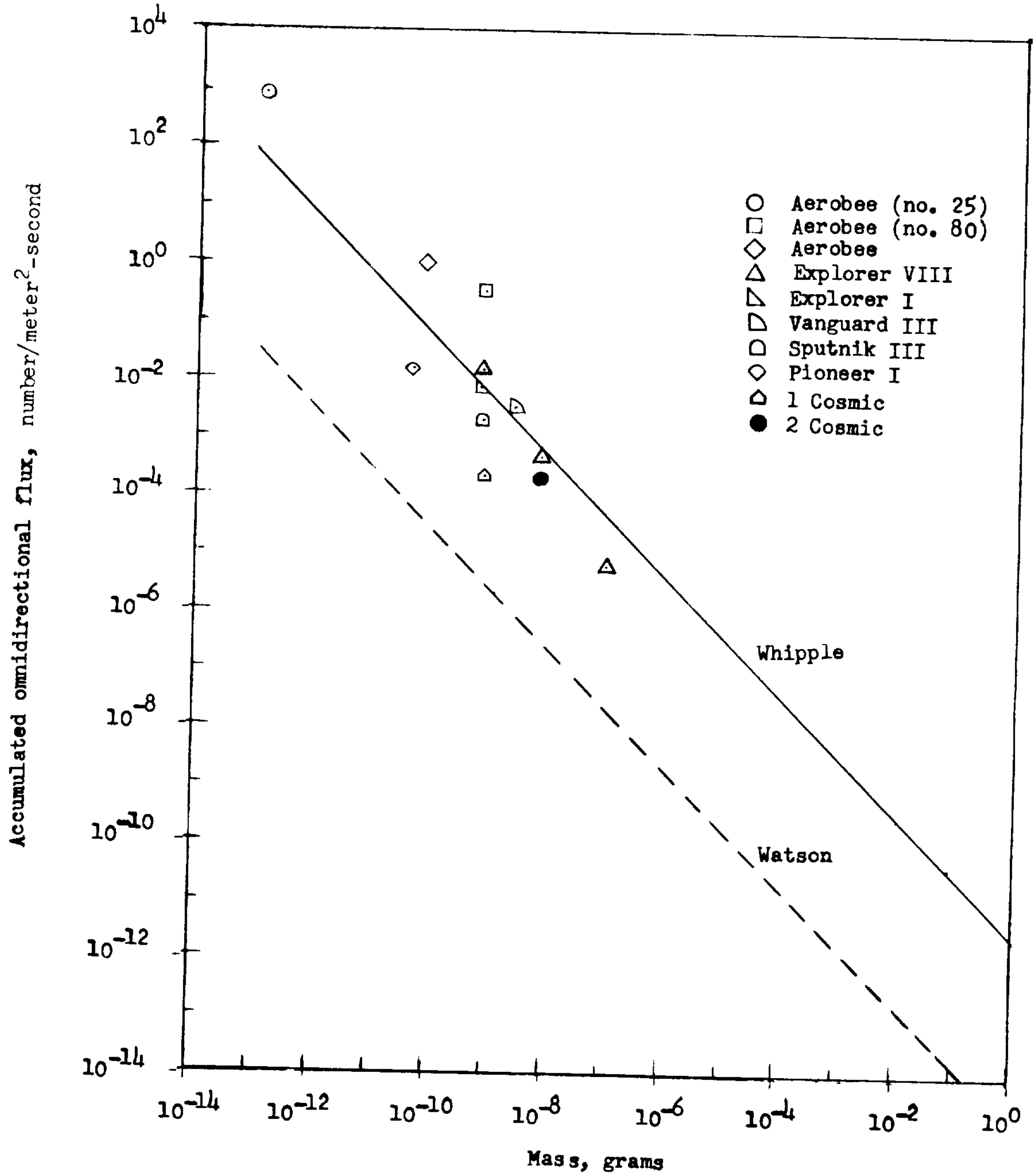

Figure 10.- Comparison of observed accumulated omnidirectional flux with Whipple's and Watson's estimated flux as a function of meteorite mass.

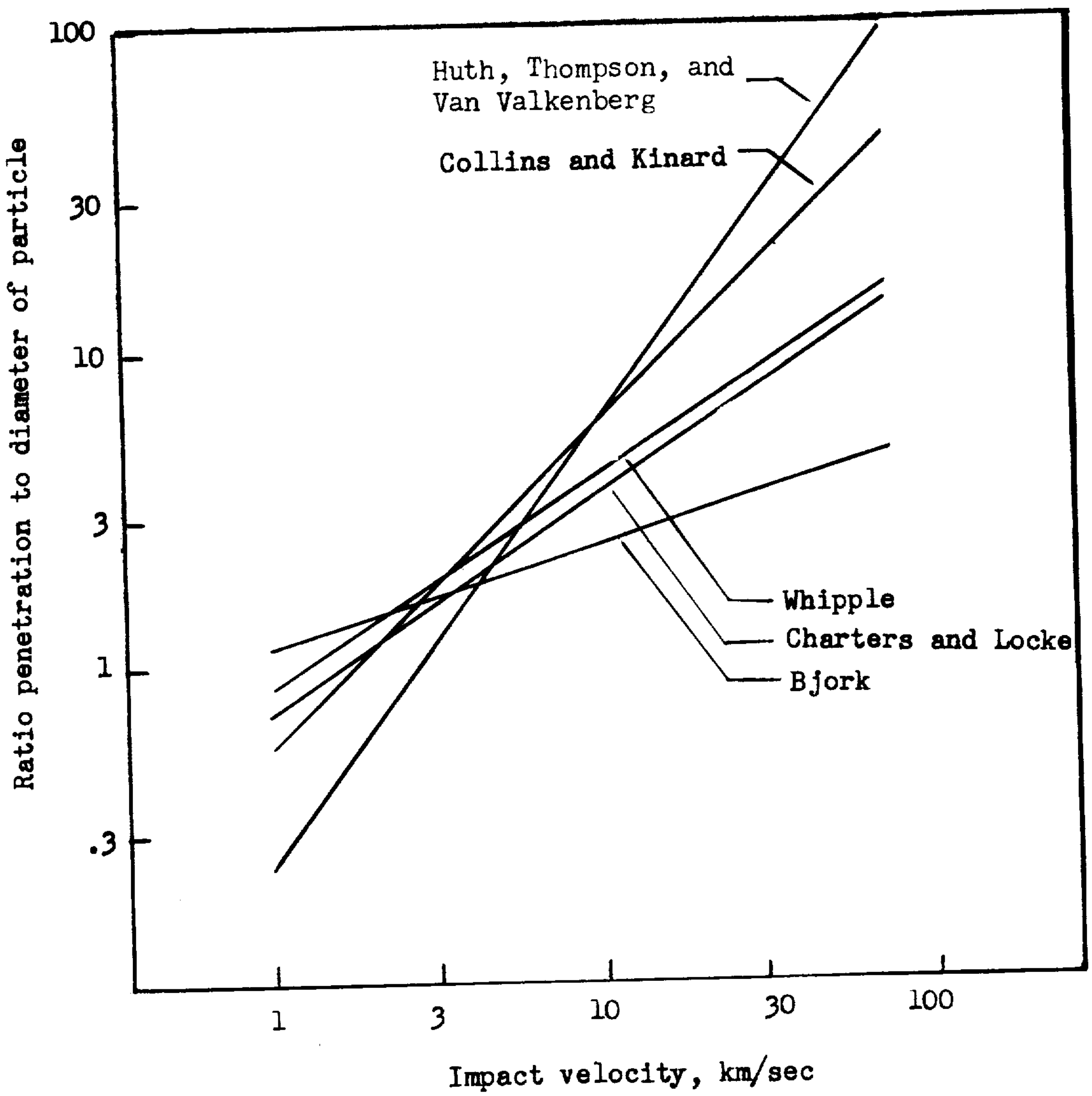

Figure 11.- Penetration estimates for steel projectile in steel targets.

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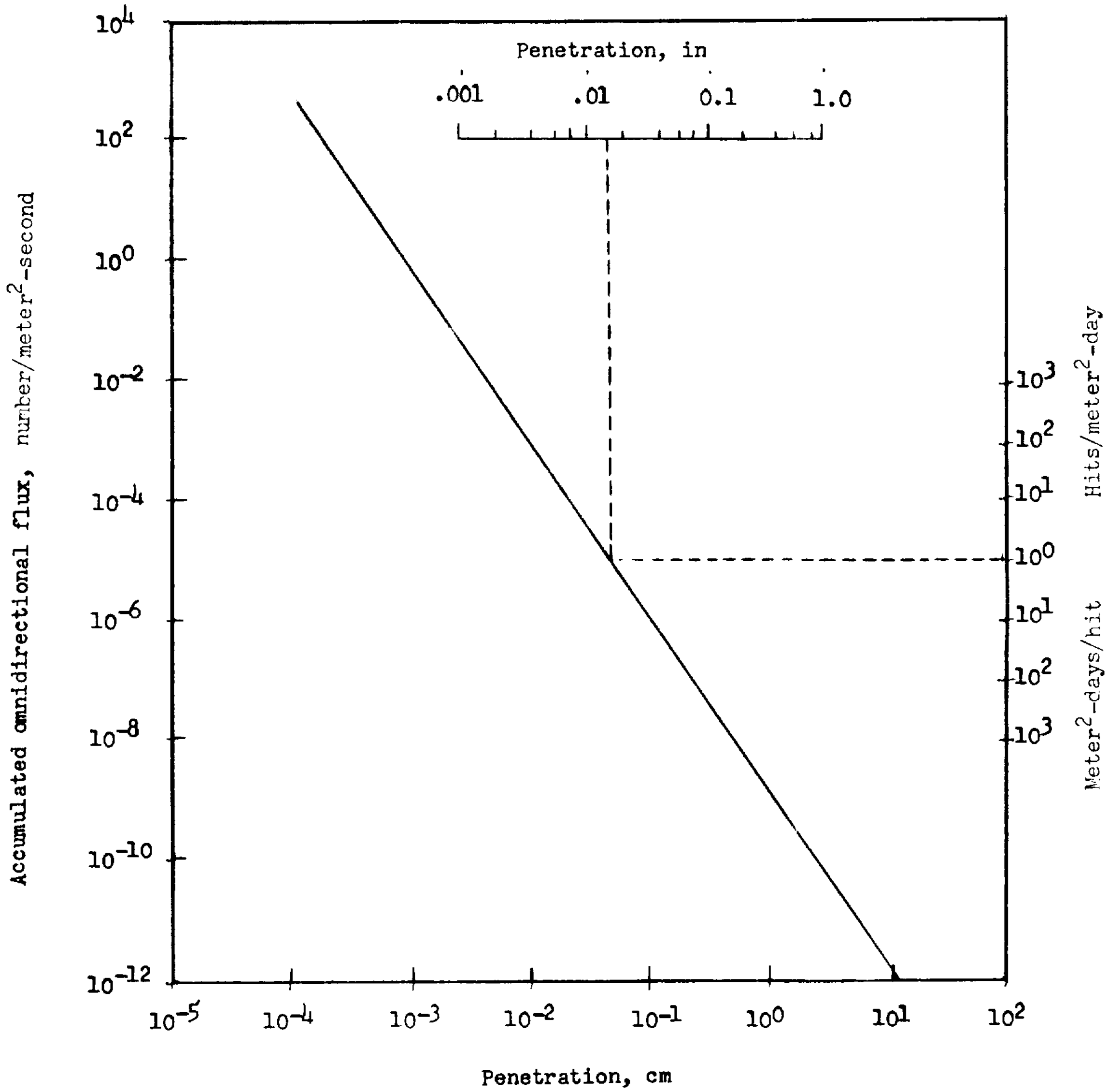

Figure 12.- Average rate of penetration.

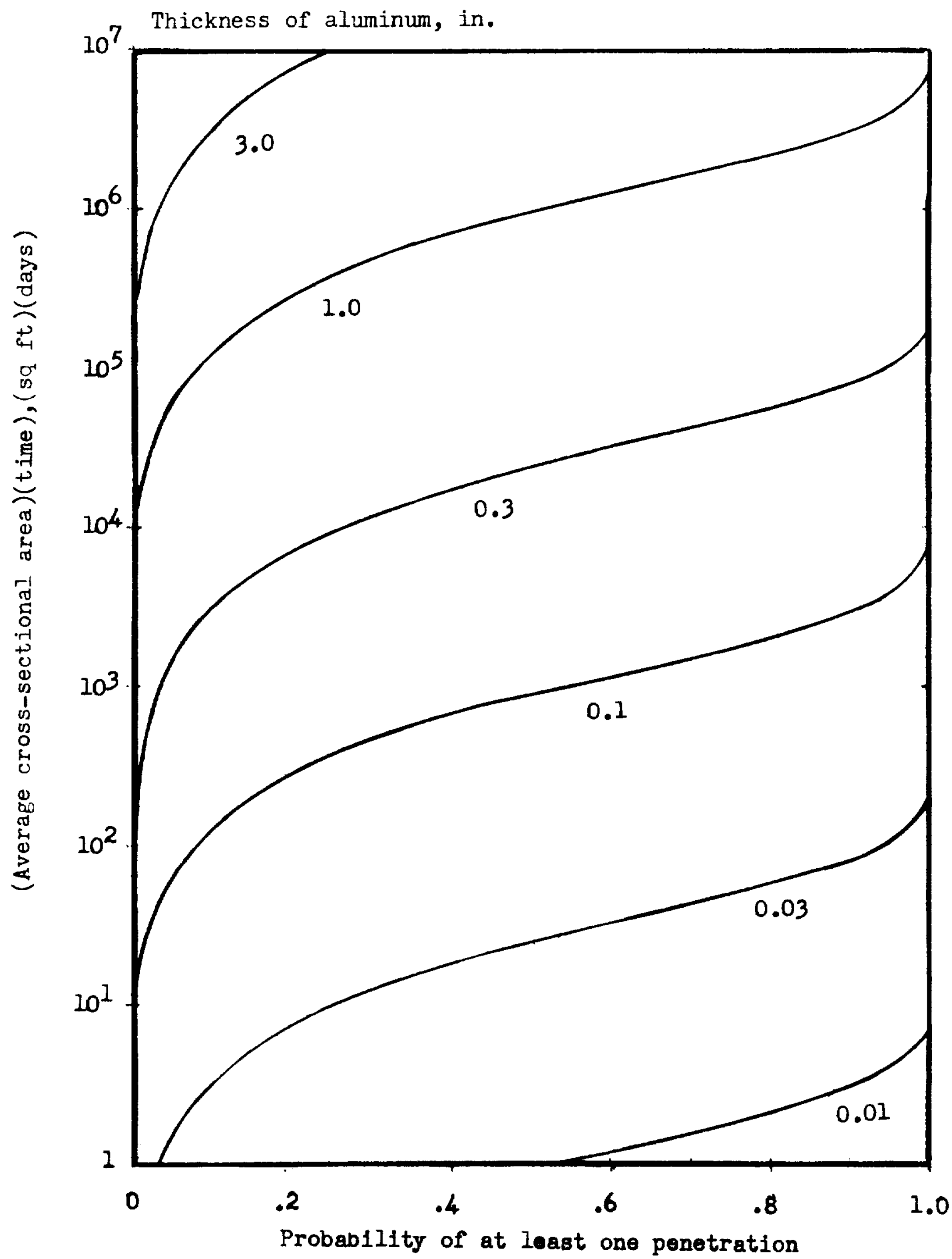

Figure 13.- Probability of puncture as a function of average cross-sectional area and time.

NASA-Langley, 1962 L-1963